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CMS

Searches for New Physics in final states with leptons or photons with CMS

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On behalf of the CMS Collaboration

EPS 2021, Worldwide

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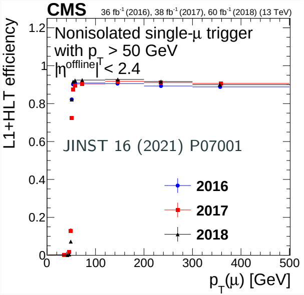
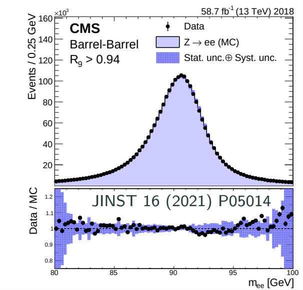
Searching for new physics with leptons and photons

- Leptons and photons are reconstructed and identified with high efficiency and precisions
  - Offers handles to suppress backgrounds and identify signs of new physics



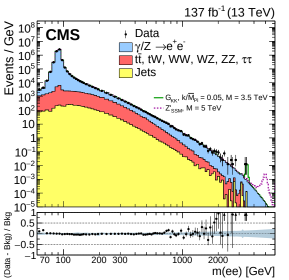


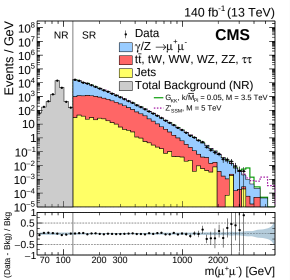
- Searches for new physics in dilepton and diphoton final states, especially at high mass, are a staple of the LHC search program
- With these searches mature and reaching the limits of their sensitivity at $\sqrt{s} = 13\,\text{TeV}$, innovative search strategies are being explored to target more complex final states and using novel analysis techniques
- Established analyses are branching out into new interpretations and indirect searches

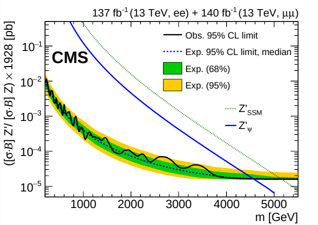
- Here I will cover recent results with prompt leptons and photons
  For searches targeting long-lived signatures, see Bryan Cardwell's talk at 16:00h

High mass dilepton pairs

- Search for a deviation from SM Drell-Yan background in high-mass dilepton pairs
- Dedicated reconstruction algorithms and IDs for TeV-scale leptons





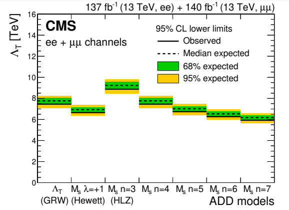


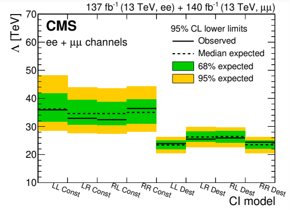
arXiv:2103.02708, submitted to JHEP

- Simple resonance search on full Run 2 dataset has been public since fall of 2019
- CMS recently published a much more detailed study with many more interpretations, including non-resonant signals

- Backgrounds estimated mostly from simulation, using Powheg corrected to NNLO QCD and NLO EWK for DY background
- Unbinning ML fit used for resonant signals, binned likelihoods used for non-resonant analysis
- Limits are set for spin-1 (up to 5.15 TeV) and spin-2 (2.47-4.87 TeV) resonances
- Lower limits on the mass of a DM mediator ranging from 1 to 4.6 TeV are set for different benchmark models

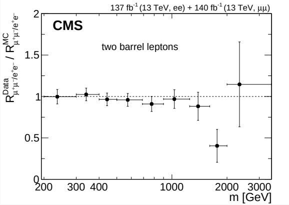
High mass dilepton pairs

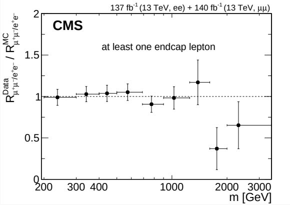




- Searched for non-resonant deviations in the mass spectrum, interpreted in a four-fermion Contact Interaction and the ADD model of extra dimensions
- Distribution of the scattering angle $\cos\theta^*$ is exploited to increase sensitivity
- Limits on the UV cutoff range from 24 to 36 TeV in the CI model and 5.9 TeV to 8.9 TeV for the ADD model

- Inspired by recent hints of lepton-flavor violation, the dielection and dimuon mass spectra are compared as a function of mass
- Spectra are unfolded to particle level and corrected for different acceptance of the two channels
- Some moderate deviations from unity at high mass, from excess events in the dielectron channel, but no smoking gun for lepton-flavor violation





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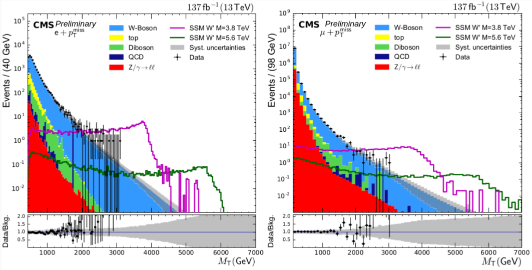
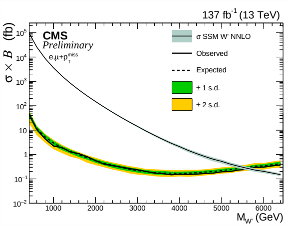
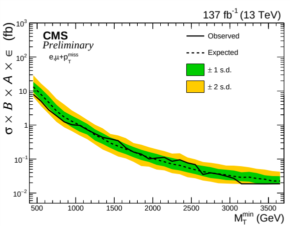
Search in lepton + E_T^{miss}



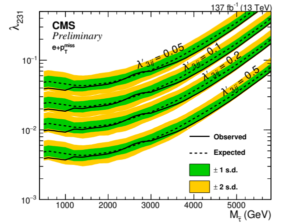
- Search for new physics in the lepton + E_T^{miss} final state
- Motivated by models with heavy gauge bosons W', excited Kaluza-Klein states or R-Parity Violating SUSY
- Targeting back-to-back signature of lepton and E_T^{miss} with cuts on lepton p_T / E_T^{miss} and the $\Delta\phi$ between them

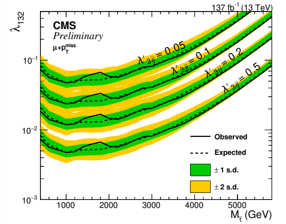
- Limits are calculated using a multi-bin shape analysis
- Limit on W'_{SSM} reaches 5.7 TeV for the combination of electron and muon channels
- Use a single-bin counting approach to provide model-independent cross section limits as a function of the lower mass cutoff

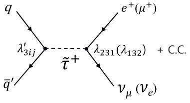




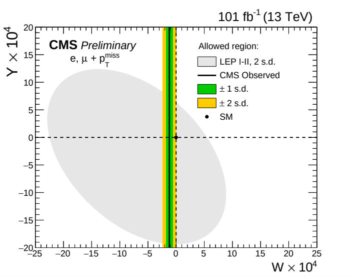
CMS-PAS-EXO-19-017







- Interpret result for $\tilde{\tau}$ production in RPV SUSY
- Limits are set on the RPV couplings λ_{231} and $\lambda 132$ for different values of the production coupling λ_{3xx}

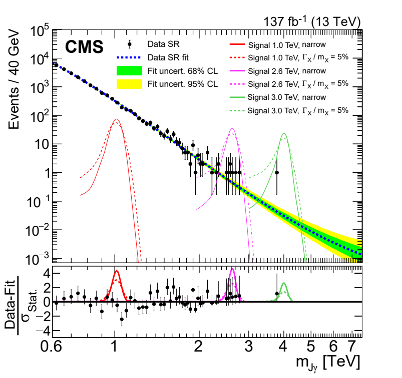


- New physics beyond the direct kinematic reach of the search could still modify the tail of the M_{T} spectrum
- Can be described in a general way using 6-dimensional operators containing the H, W, and B fields
- High mass behavior sensitive to the parameters Y and W (https://arxiv.org/abs/1609.08157)
- With this search, the W parameter can be constraint significantly compared to previous LEP results

CMS-PAS-EXO-19-017

$W\gamma$ resonances

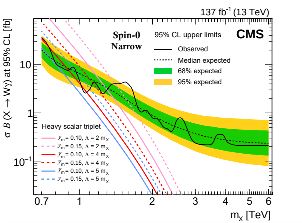
- $W\gamma$ resonances are predicted in a variety of models with extended Higgs sectors, technicolor models, or folded supersymmetry
- Analysis targets hadronic decays of heavily boosted Ws, reconstructed as large-radius jets indentified using the soft-drop jet mass and the N-subjettiniess ratio τ_{21}
- Signal further separated from the dominant γ+jets background using η_γ, η_J, the scattering angle $\cos\theta^*_\gamma$ and the ratio of p_T^γ to $m_{J\gamma}$

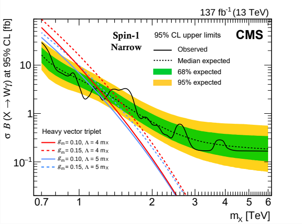


- Signal acceptance $\times$ efficiency ranges between 6 and 12% for spin-0 and 10 and 16% for spin-1 particles
- Background is modeled with a analytical function chosen to balance goodness-of-fit with the number of free parameters
- Signal modeled with a Crystal Ball summed with one (narrow resonances) or two (5% width) Gaussians

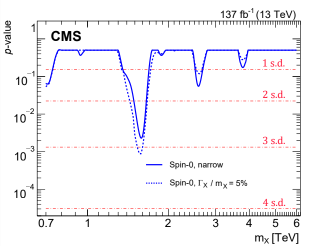
arXiv:2106.10509, submitted to PLB

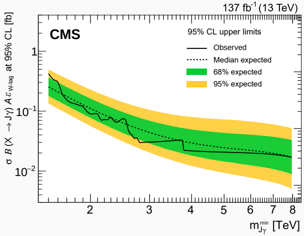
$W\gamma$ resonances





- $\approx 3\,\sigma$ deviation observed at 1.58 TeV. Corrected for look-elsewhere-effect, this reduces to 1.1-1.7 σ, depending on the width
- Limits are set for spin-0 and spin-1 signals for narrow and wide resonances
- In scalar (vector) triplet benchmark models, the excluded mass range is 0.75-1.4 (1.15-1.35) TeV
- Model independent limits as a function of the lower mass cutoff are also provided





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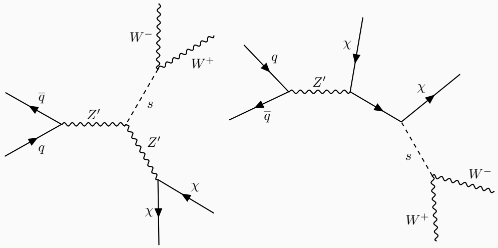
Dark Matter in association with Dark Higgs

- NEW for EPS

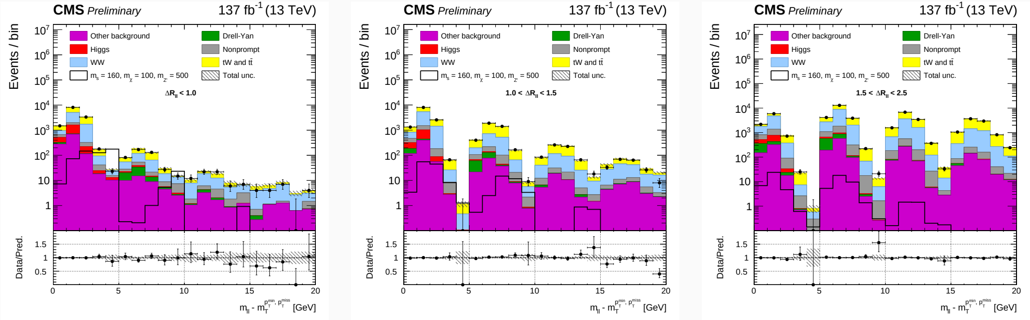


- In scenarios where DM particles acquire mass via a Dark Higgs boson s, these could be produced at the LHC in association with the DM particles
- This analysis focuses on decays s $\rightarrow$ WW, with further leptonic decays of the W bosons

- Events with two leptons with $m_{\ell\ell} >$20 GeV and $p_{\mathrm{T}}^{\ell\ell} >$30 GeV are selected
- WZ and ZZ, as well as $\mathrm{t\bar{t}}$ are reduced by vetoing third leptons and b-jets
- DY backgrounds are further rejected with requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and how it aligns with the leptons

CMS-PAS-EXO-20-013

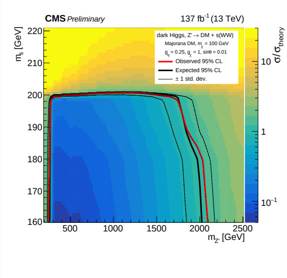
Dark Matter in association with Dark Higgs

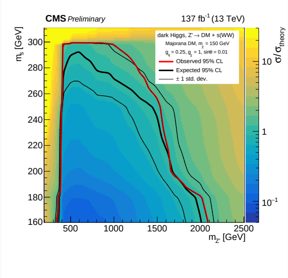


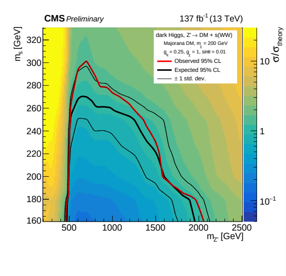
- Event sample is split into three bins of $\Delta R(\ell\ell)$, which are in turn split into multiple bins in $m_{\ell\ell}$ and transverse mass $m_{\mathrm{T}}(\ell^{p_{\mathrm{T}},min}, E_{\mathrm{T}}^{\mathrm{miss}})$
- Background estimate mostly from MC (except non-prompt leptons)
- MC sample normalization obtained from dedicated data control regions for the DY, WW, and top backgrounds

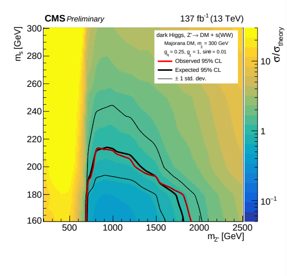
CMS-PAS-EXO-20-013

Dark Matter in association with Dark Higgs









- Limits are set in the $m_{Z'} - m_s$ plane for different values of m_χ
- Most stringent limits are set for $m_\chi = 150$ GeV, where m_s masses up to 300 GeV are excluded for $480 < m_{Z'} < 1200$ GeV
- Highest limit on $m_{Z'}$ reaches 2 TeV for $m_s = 160$ GeV

CMS-PAS-EXO-20-013

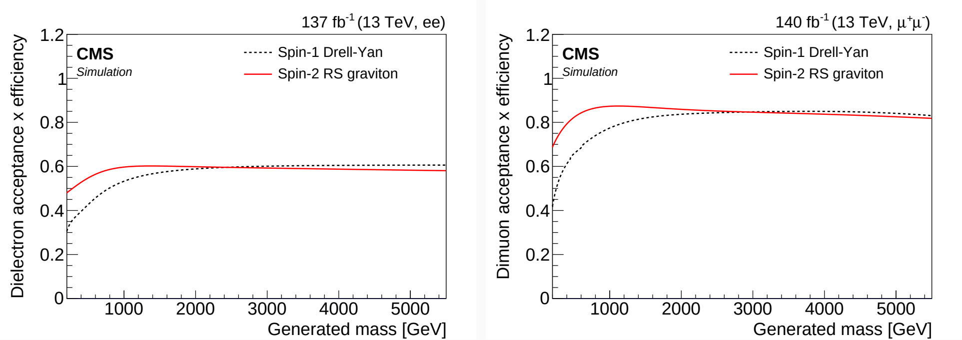
Summary

- Final states with leptons and photons offer great sensitivity to many models of new physics
  - High efficiency and great momentum/energy resolution helps suppress backgrounds
- Analyses using these objects range from very simple dilepton signatures to significantly more complex final states
- Analyses with more simple final states are often quite mature and expanding to unconventional interpretations and adding novel measurements
- Similarly, new final states are explored, constantly expanding the phase space coverage of the CMS search program

- Only four recent examples shown here. Many more results as well as summary plots are available at `http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html`

Additional Material

High mass dilepton - acceptance × efficiency



High mass dilepton - Systematic uncertainties

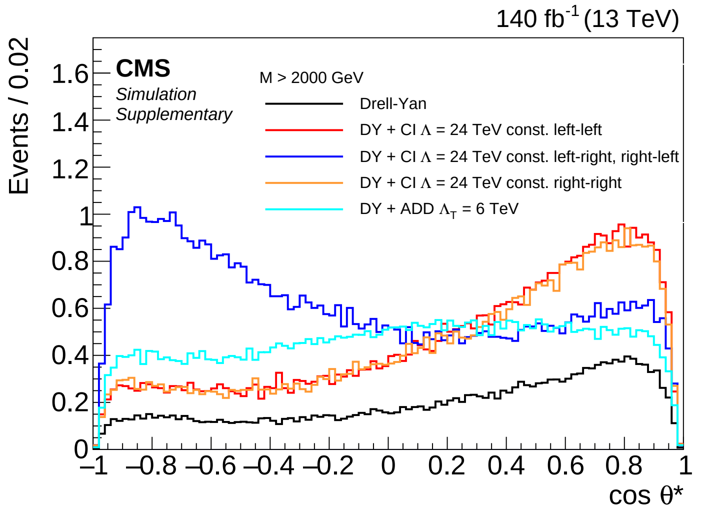
Source	Uncertainty
Electron selection efficiency	6–8%
Muon selection efficiency	1–2% (two-sided), 0–6.5% (one-sided)
Mass scale uncertainty	1–3%
Dimuon mass resolution uncertainty	8.5–15%

Figure 1: Uncertainties for resonance search

Uncertainty source	Impact on background [%]			
	$m_{ellell} > 1$ TeV		$m_{ellell} > 3$ TeV	
	ee	$\mu\mu$	ee	$\mu\mu$
Lepton selection efficiency	6.8	0.8	6.4	1.3
Muon trigger efficiency	—	0.9	—	0.9
Mass scale	7.0	2.7	15.4	2.4
Dimuon mass resolution	—	0.1	—	0.6
Pileup reweighting	0.3	—	0.5	—
Trigger prefiring	0.5	—	0.2	—
PDF	3.7	3.0	9.4	10.2
Cross section for other simulated backgrounds	0.6	0.8	0.2	0.4
Z peak normalization	2.3	5.0	2.0	5.0
Simulated sample size	0.4	0.4	1.3	1.6

Figure 2: Uncertainties for non-resonant search

High mass dilepton - Scattering angle



Lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$- Tables

- Event yield in the electron, muon, and combined channel

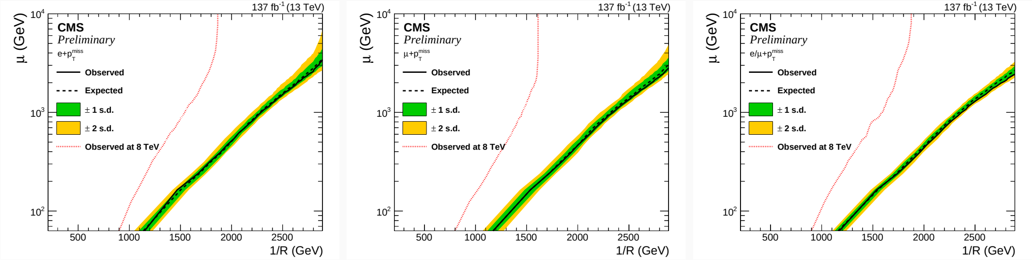
	$M_{\mathrm{T}} > 1.0$ TeV	$M_{\mathrm{T}} > 2.0$ TeV	$M_{\mathrm{T}} > 3.0$ TeV	$M_{\mathrm{T}} > 4.0$ TeV
Electron data	831	23	1	0
Total SM backgrounds	835 ± 64	21.1 ± 2.5	1.16 ± 0.24	0.066 ± 0.029
SSM W′ M = 3.8 TeV	211 ± 35	155 ± 29	93 ± 20	1.95 ± 0.68
SSM W′ M = 5.6 TeV	8.0 ± 2.1	4.8 ± 1.7	3.5 ± 1.5	2.5 ± 1.3
Muon data	829	21	0	0
Total SM backgrounds	805 ± 83	21.7 ± 2.9	1.05 ± 0.34	0.089 ± 0.040
SSM W′ M = 3.8 TeV	192 ± 28	141 ± 24	80 ± 19	6.4 ± 1.8
SSM W′ M = 5.6 TeV	11.0 ± 1.6	6.6 ± 1.1	4.6 ± 1.1	3.2 ± 0.9

- Limit summary

Model	**Parameter**	**Channel**	**Observed Limit (Expected Limit)**
SSM W′	$M_{\mathrm{W'}}$ ($g_{\mathrm{W'}}/g_W = 1$)	e	$M_{\mathrm{W'}} < 5.4$ TeV (< 5.3 TeV)
		μ	$M_{\mathrm{W'}} < 5.6$ TeV (< 5.5 TeV)
		e + μ	$M_{\mathrm{W'}} < 5.7$ TeV (< 5.6 TeV)
split-UED $\mathrm{W}_{\mathrm{KK}}^{(2)}$	$1/R$ (if $\mu = 2$ TeV)	e	$1/R < 2.7$ TeV (< 2.6 TeV)
		μ	$1/R < 2.7$ TeV (< 2.7 TeV)
		e + μ	$1/R < 2.8$ TeV (< 2.7 TeV)
RPV SUSY $\tilde{\tau}$	$\lambda_{\mathrm{decay}=231,132}$ (if $\lambda'_{3ij} = 0.5$, $M_{\tilde{\tau}} \approx 1$ TeV)	e	$\lambda_{231} > 3.7 \times 10^{-3}$ ($> 4.6 \times 10^{-3}$)
		μ	$\lambda_{132} > 4.7 \times 10^{-3}$ ($> 4.7 \times 10^{-3}$)
EFT	W oblique parameter	e + μ	Best-Fit $W = -0.00012^{+0.00005}_{-0.00006}$

Lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$- split-UED limits

- Spacetime extended by an additional dimension of radius R
- Signature: Kaluza-Klein excitations of the W boson with mass $M(\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}) = \sqrt{M_{\mathrm{W}}^2 + (\mathrm{n}/\mathrm{R})^2}$
- Additional parameter: bulk mass parameter μ



Wγ - Selection

Hadronic W

- anti-k_{T} jets with $R = 0.8$, $p_{\mathrm{T}} > 225\,\mathrm{GeV}$, $\Delta R(\mathrm{jet}, \gamma) > 1.1$
- Corrected for PU using PUPPI
- Groomed with soft drop ($\beta = 0$, $z_{\mathrm{cut}} = 0.1$)

Signal region definition

- $68\,\mathrm{GeV} < m_{\mathrm{j}}^{SD} < 94\,\mathrm{GeV}$
- $|\eta_{\gamma}| < 1.44$
- $|\eta_{\mathrm{J}}| < 2.0$
- $\tau_{21} < 0.35$
- $p_{\mathrm{T}}^{\gamma}/m_{\gamma\mathrm{J}} > 0.37$
- $\cos\theta_{\gamma}^{*} < 0.6$

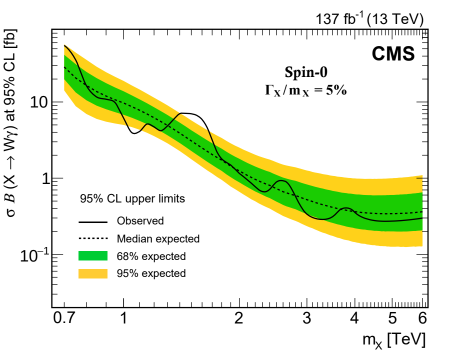
Wγ - Systematic uncertainties

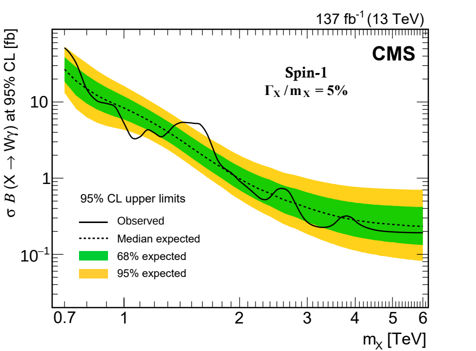
- Limits for resonances with a width of 5%

Source	Effect on the signal yield (%)	Combined (%)
Integrated luminosity	2.5/2.3/2.5	1.8
Trigger efficiency	1.0/2.3/1.0	0.9
Photon ident. efficiency	4.7/6.0/3.0	4.4
Pileup	1.0/2.0/1.0	1.3
PDF	2.0	2.0
Wtagging efficiency	11/7.4/3.2	3.9
Jet energy scale and resolution†	1.3	0.8
Photon energy scale and resolution†	0.5/1.0/1.0	0.9
Total	12.6/10.6/5.8	6.7

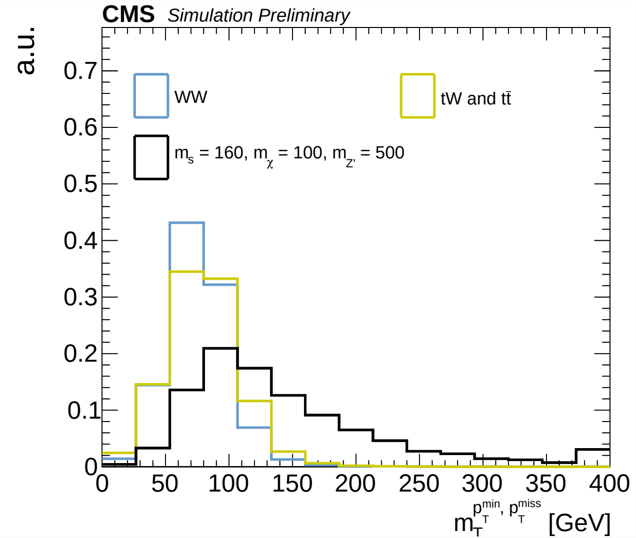
Wγ - wide resonance limits

- Limits for resonances with a width of 5%





Dark Higgs - $M_{\mathrm{T}}(p_{\mathrm{T}}^{min}, E_{\mathrm{T}}^{\mathrm{miss}})$



Dark Higgs - Selection

Quantity	Selection
Number of leptons	2
Lepton flavors	eμ, μe
Lepton charges	Opposite
Additional leptons	0
$p_{\mathrm{T}}^{\ell\,\mathrm{max}}$	> 25
$p_{\mathrm{T}}^{\ell\,\mathrm{min}}$	> 20
$m_{\ell\ell}$	> 12
$p_{\mathrm{T}}^{\ell\ell}$	> 30
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 20
$p_{\mathrm{T,proj}}^{\mathrm{miss}}$	> 20
$m_{\mathrm{T}}^{ll,p_{\mathrm{T}}^{\mathrm{miss}}}$	> 50
$\Delta R_{\ell\ell}$	< 2.5
Number of b-tagged jets	0

- $\Delta R(ll)$ binning: [0,1.0,1.5,2.5]
- $m_{\ell\ell}$ binning: 12,60,90,120,inf] GeV
- $M_{\mathrm{T}}(p_{\mathrm{T}}^{min}, E_{\mathrm{T}}^{\mathrm{miss}})$ binning: ([0,50,90,130,160,inf] GeV, [0,50,90,130,170,inf] GeV, and [0,50,90,130,180,inf] GeV for 2016, 2017, and 2018 respectively